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A PROCESSING TECHNIQUE FOR SYMMETRIC SIGNALS,(U)
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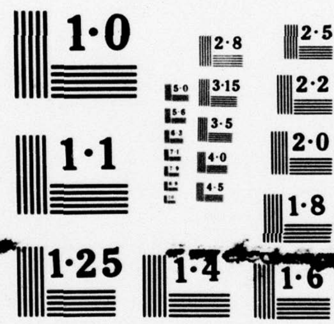

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6 A PROCESSING TECHNIQUE FOR SYMMETRIC SIGNALS,

by

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EQUAL TO OR LESS THAN

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ABSTRACT

A symmetric signal $S(t)$, $-T \leq t \leq T$, is one for which $S(t)=S(-t)$. Such symmetrics are independent of Doppler effects and thus of interest in certain applications. A correlation-like processing technique is described here that capitalizes on this symmetry property.

TABLE OF CONTENTS

A PROCESSING TECHNIQUE FOR SYMMETRIC SIGNALS

G. S. Innis

I. INTRODUCTION

If $S(t)$ is defined for $-T \leq t \leq T$ and $S(t)=S(-t)$, $-T \leq t \leq T$, then $S(t)$ is symmetric and this symmetry is invariant under Doppler shifts. A correlation-like processing technique is described below that takes advantage of the symmetry of the signal. This technique is compared with the ordinary correlator for various correlator lengths, input signal-to-noise ratios, and Doppler shifts.

A. Symmetric Signal Correlator

Let $S(t)$ be a symmetric signal defined on the interval $-T \leq t \leq T$. If such a signal is passed through a medium whose effect on the signal is linear, bounced off of a simple target moving at a speed V relative to the transmitter, passed back through the medium, the resulting signal

$$R(t) = AS(bt - \Delta) \tag{1}$$

is still symmetric about some delay time Δ. Thus if we limit our discussion to the symmetry properties of the received signal, there is no loss in replacing $R(t)$ by $S(t)$. It should be recalled, however, that $R(t)$ exists for the period $2T$ only if $b=1$, i.e., if $V=0$. In general $R(t)$ will exist for the period $2(1 - \frac{2V}{c})\ T$ where c is the speed of transmission in the medium of interest. Let us ignore for the moment this change of period.

In any practical problem the signal at each of the three steps--transmission, reflection, and return -- is corrupted by noise. We shall assume that this noise, N, is uncorrelated with the signal and additive. (One additional noise feature is required later.) Therefore, the returning signal is essentially

$$X(t) = AS(t) + \dot{N}(t) \quad . \tag{2}$$

If the noise background is white over the band of frequencies in which the signal makes significant contributions, a reasonable technique for locating the signal is to compute

$$C(\tau) = \int_{-T}^{T} X(t - \tau)S(t)\,dt \quad , \tag{3}$$

the cross correlation of S with X. The primary difficulty with this approach is that S(t) must be known; i.e., b must be known.

One can, however, also use the symmetry of S at this point and instead of using Eq. (3) compute:

$$SP(\tau) = \int_{-T}^{T} X(\tau + t)\, X(\tau - t)\,dt \quad . \tag{4}$$

If the signal X is of the form given by Eq. (2), then

$$\begin{aligned} SP(\tau) = \int_{-T}^{T} \Big\{ & A^2 S(\tau + t)\, S(\tau - t) + AS(\tau + t)N(\tau - t) \\ & + AS(\tau - t)N(\tau + t) + N(\tau + t)N(\tau - t) \Big\} dt \quad . \end{aligned} \tag{5}$$

It is in reducing Eq. (5) that an additional assumption about the noise is convenient. Assuming that the noise is uncorrelated with the time inverse of the signal and with the time inverse of the noise over the period 2T, then the last three terms of Eq. (5) are negligible when compared to the first term, and we have

$$SP(\tau) \cong A^2 \int_{-T}^{T} S(\tau + t)S(\tau - t)\,dt \quad . \tag{6}$$

Thus if S is a suitably chosen symmetric signal the significant portion of SP will occur when $\tau = 0$. (For example, S could be formed be time reversing a portion of a broadband noise signal S and combining the reversed portion with S_1 to form a symmetric signal.)

If S is known the disadvantage of this approach stems from the fact that all available prior knowledge is not being used. Some results presented below indicate the extent to which this degradation occurs for various input signal-to-noise ratios.

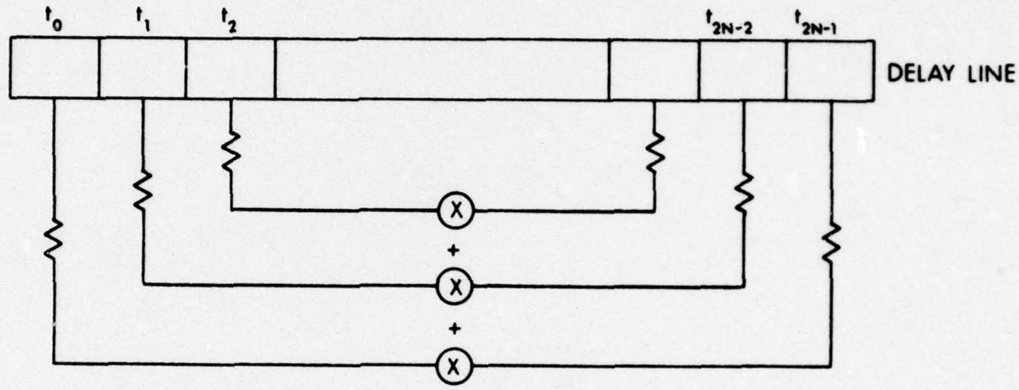
The advantages of this approach are several and may, for certain applications, outweigh the disadvantage.

1. Less a priori knowledge is required. In a one-way communication system the messages could be coded in bursts with their inverses and transmitted at differing frequencies. The received signal could be recorded, processed as above to locate the signals and the time inverses of the messages used to correct errors in the message.

2. In sonar and radar type applications the symmetric signals might be properly coded to decrease the probability that the target would realize observations were being made. A low-level symmetric signal derived from a broadband noise source would almost certainly not be observed by a target, particularly if the signal and band were being constantly changed (neither change affects the process).

3. The process is extremely simple to implement. For example, if a tapped delay line is available, the values for small delay are multipled by the values for large delay and the products added, as indicated in Fig. 1. It is quite simple to attach the device to some existing correlators.

4. The process is Doppler insensitive for most practical purposes. The relative target speed V effects the length of the received signal as indicated. If V/c is small, as is usual, this effect is small and of little consequence. Thus for the normal range of Dopplers, only a single processor for the returned signal is required, as opposed to the comb filters and banks of correlators presently being used.



$$\sum_{\iota=0}^{N-1} \times (t_\iota) \times (t_{2N-\iota+1}) = 1/2 \text{ NC}$$

FIGURE 1
TAPPED DELAY - LINE IMPLEMENTATION OF NC.

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B. Description of Experiments

In order to test the ideas discussed above, a computer program was written for the Defense Research Laboratory Control Data 3200 Computer System. This program, listed in Appendix I, constructs a symmetric signal from a portion of a Gaussian white digital noise signal. This symmetric signal is then Doppler shifted, amplified, and added back into the noise source forming the simulated received signal X(t) (see Fig. 2).

The simulated received signal is then processed in a finite approximation to Eq. (3') and (4').

$$C'(I) = \sum_{1}^{n} S(J)\, X(I + J - 1) \quad , \text{ and} \tag{3'}$$

$$SP'(I) = \sum_{1}^{n} X(I + J - 1)\, X(I + N - J) \tag{4'}$$

where

S is the symmetric signal prior to Doppler shifting.

The parameters used in the experiments performed to date include

Q = 128	A = 0.5	V = 0.0 kt
256	1.0	3.0 kt
512	1.5	15.0 kt

where

the symmetric signal is of length Q if V = 0.0, and

A is the ratio of peak signal to peak noise.

For each set of parameters, several (usually 4) distinct received waveforms were generated and processed. The data displayed in Table I are computed by averaging these distinct runs.

The signal-to-noise ratios quoted in Table I are computed as (1) 20 log A for input and (2) 20 log B for output where B is the square root of the signal output squared divided by the mean squared background level. The merits (or lack of same) for these definitions of signal-to-noise are of no interest here since they are used strictly for comparing the output of Eq. (3') with the

TABLE I

FIXED	Q = 128		Q = 256	Q = 512
V = 0.0	A=0.5	13.37614	16.10327	18.82531
	A=1.0	16.30599	19.01318	22.04025
	A=1.5	16.32568	19.67108	22.94062
V = 3.0		12.21549	13.93880	11.36126
		15.84327	17.61457	16.07554
		16.13487	18.59193	17.70164
V = 15.0		-0.63670	-0.59502	-16.42575
		7.88371	6.07062	-0.74867
		9.03971	7.89732	3.12739
SP				
		3.43781	6.59818	6.42983
		12.48198	14.87606	17.30332
		15.66423	17.95448	20.65083

AVERAGE SIGNAL/NOISE

LINEAR

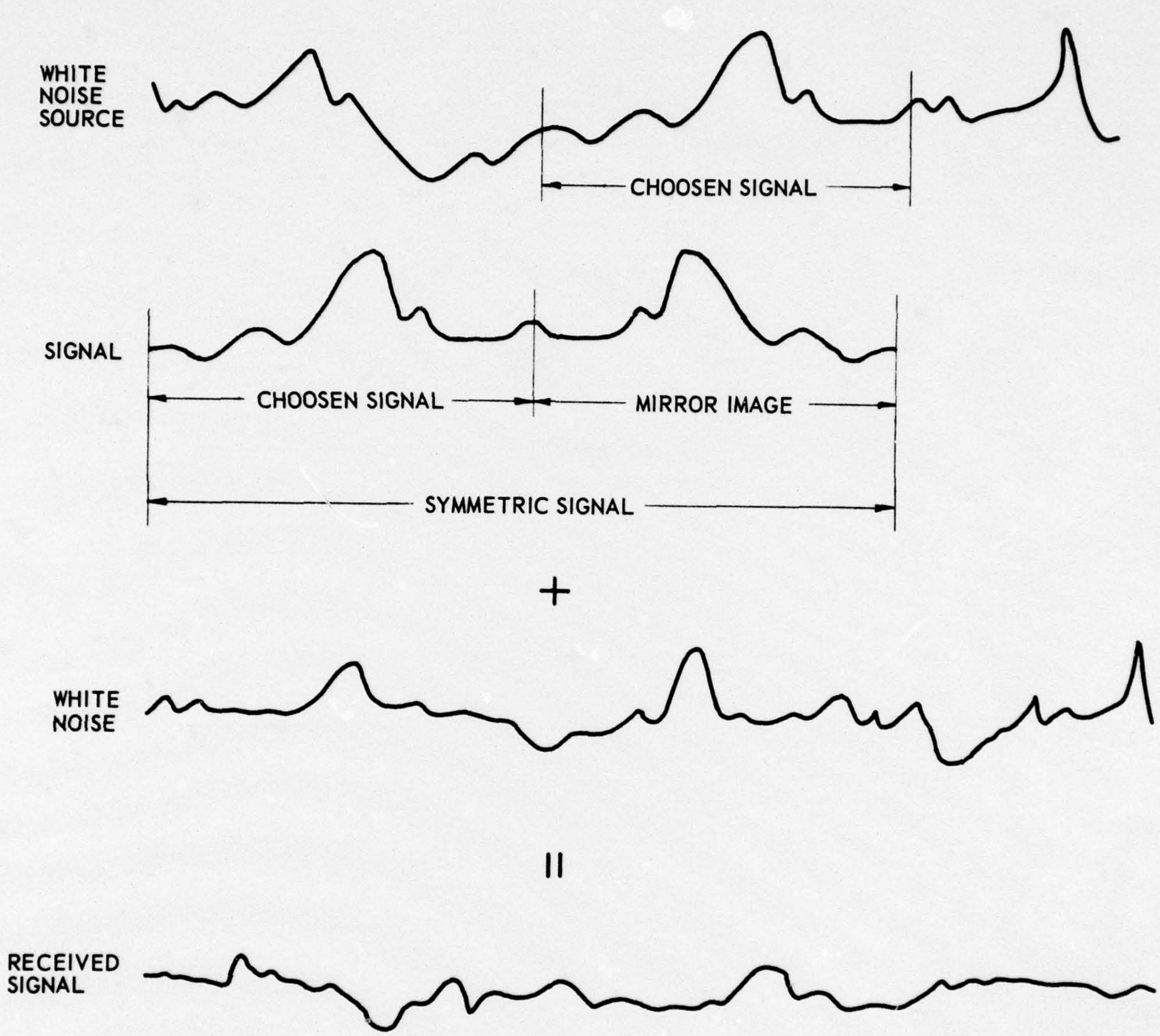

FIGURE 2
SIGNAL FORMATION PROCESS EXCEPTING
DOPPLER SHIFT AND AMPLIFICATION

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output of Eq. (4'). Several points should be noticed on examining Table I. First, even at 15 kt the effect of Doppler on the output of Eq. (4') is in the third decimal place, and consequently only a single value is displayed. Second, the new device is, without exception, poorer than the correlator, clipped or otherwise, for V=0.0. This is the effect of less a priori knowledge. Third, the performance of the correlator improves with increasing Q for low Dopplers and is degraded with increasing Q for high Dopplers. Finally, the Doppler does not have to grow very large before the correlator performance has fallen below that of Eq. (4').

Table II gives data similar to Table I except for hard-clipped processing.

Figure 3 shows three typical signals of the type used in this study. In Fig. 4 the effects of varying the amplitude A are shown for a linear correlator (LC) and a linear symmetric processor (LSP). It is evident (Fig. 4) that the background is generally higher for the LSP than for the LC. Figure 5 shows the effects of varying A for a clipped correlator (CC) and a clipped symmetric processor (CSP). The input signals for Fig. 5 are identical to those for Fig. 4.

In Fig. 6 the amplitude and velocity are fixed and the length is changed for the LC and for the LSP. The apparent reduction in background is a result of normalization - only relative amplitudes for one Q are significant. Figure 7 shows results similar to those of Fig. 6 except for the CC and for the CSP.

In Fig. 8 Doppler effects are displayed. The top three samples are for closing speeds of 0.0, 3.0 and 15.0 kt and the LC. The last trace is the output from the LSP for any of these speeds since Doppler effects were not even detectable at these low speeds. In Fig. 9 results for CC and CSP are shown for the same speeds.

C. Extended Returns

One of the interesting and difficult problems encountered in many systems of the type discussed here is that of an extended target. The preceding

TABLE II

FIXED		Q = 128	Q = 256	Q = 512
	A=0.5	10.65231	12.46188	15.66840
V = 0.0	A=1.0	15.48440	17.34189	20.60704
	A=1.5	17.11765	19.12644	22.32464
		9.47246	10.48453	6.30336
V = 3.0		14.55291	15.58354	13.05294
		16.35579	17.67445	15.47404
		0.79537	-6.14181	-3.54417
V = 15.0		6.36361	3.65706	-4.16660
		9.02937	7.44636	-3.37988
SP				
		-6.78534	-2.87917	5.05060
		8.80549	11.31279	14.22857
		12.60405	15.12193	17.40221

AVERAGE SIGNAL/NOISE

CLIPPED

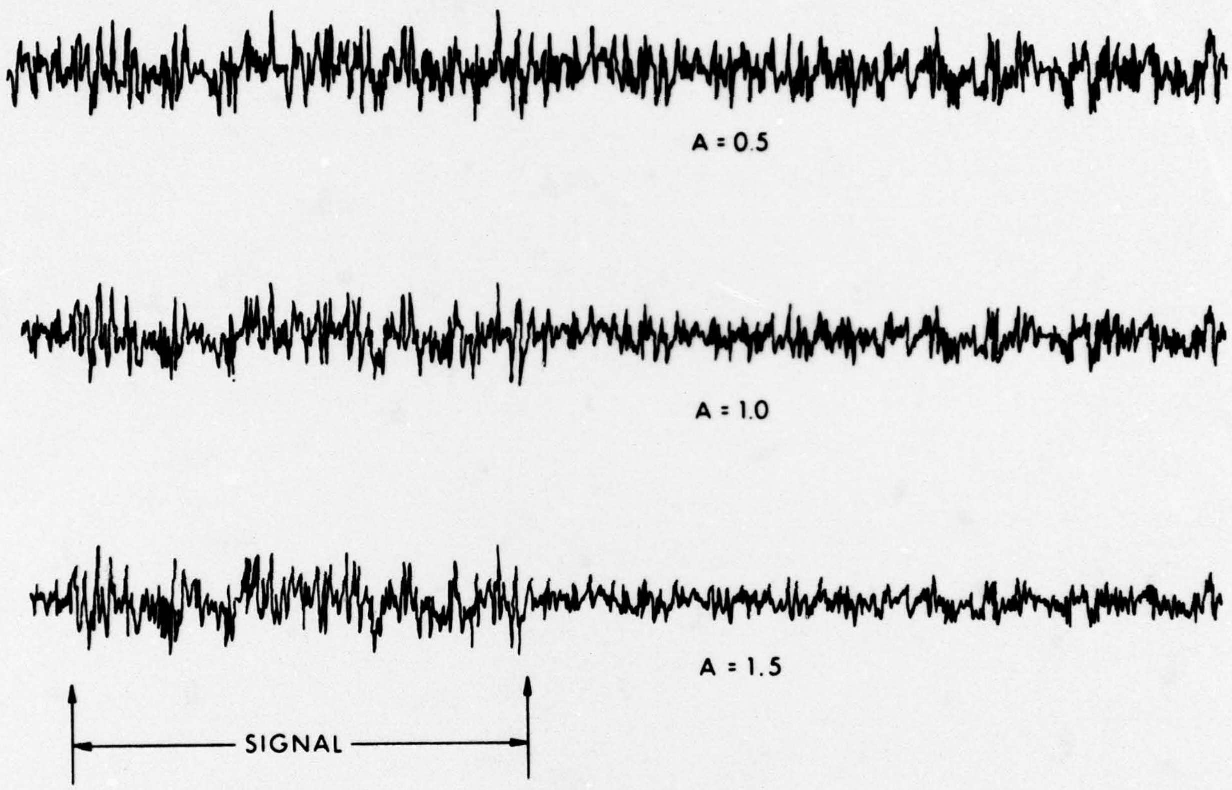

FIGURE 3
TYPICAL SIGNALS
Q = 256

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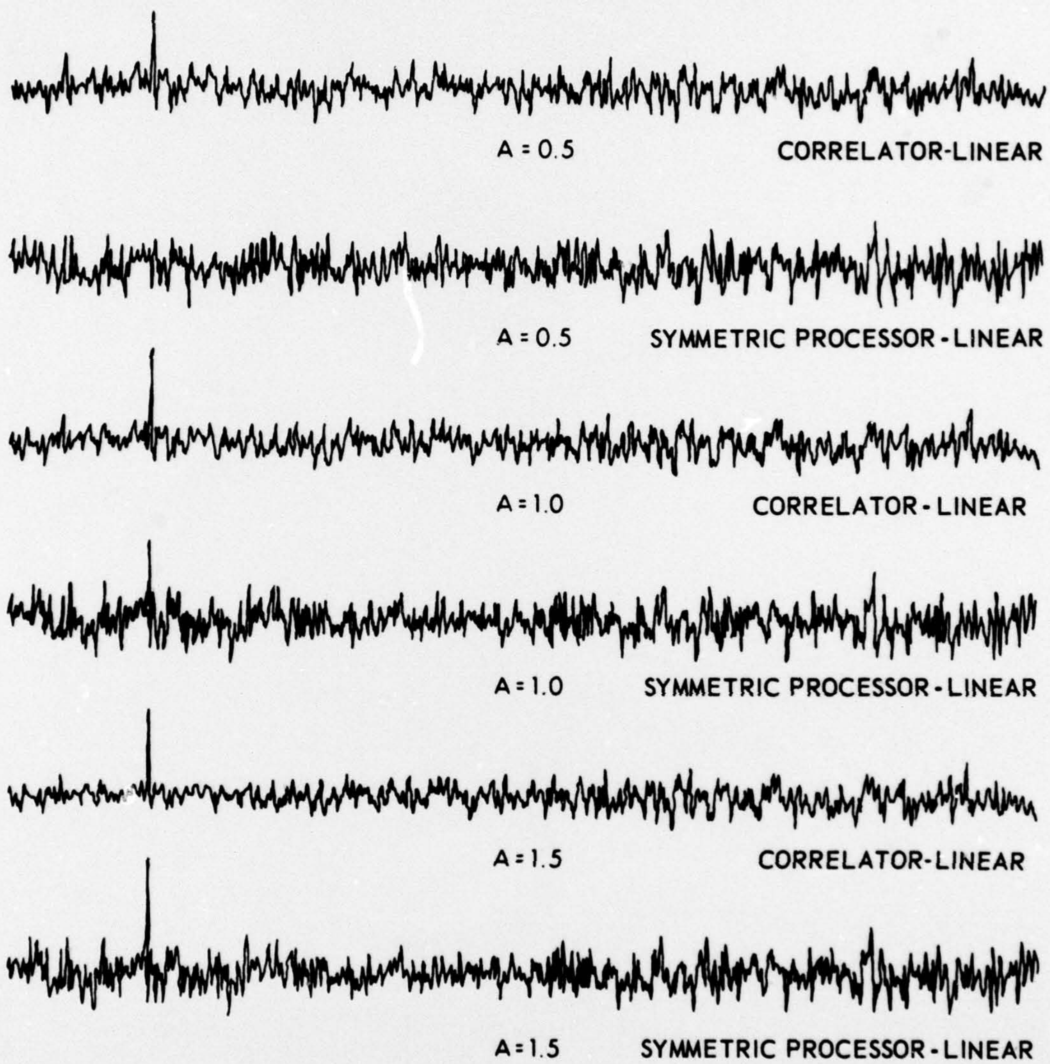

FIGURE 4
SIGNAL - TO - NOISE EFFECTS
Q = 256

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GSI - RFO
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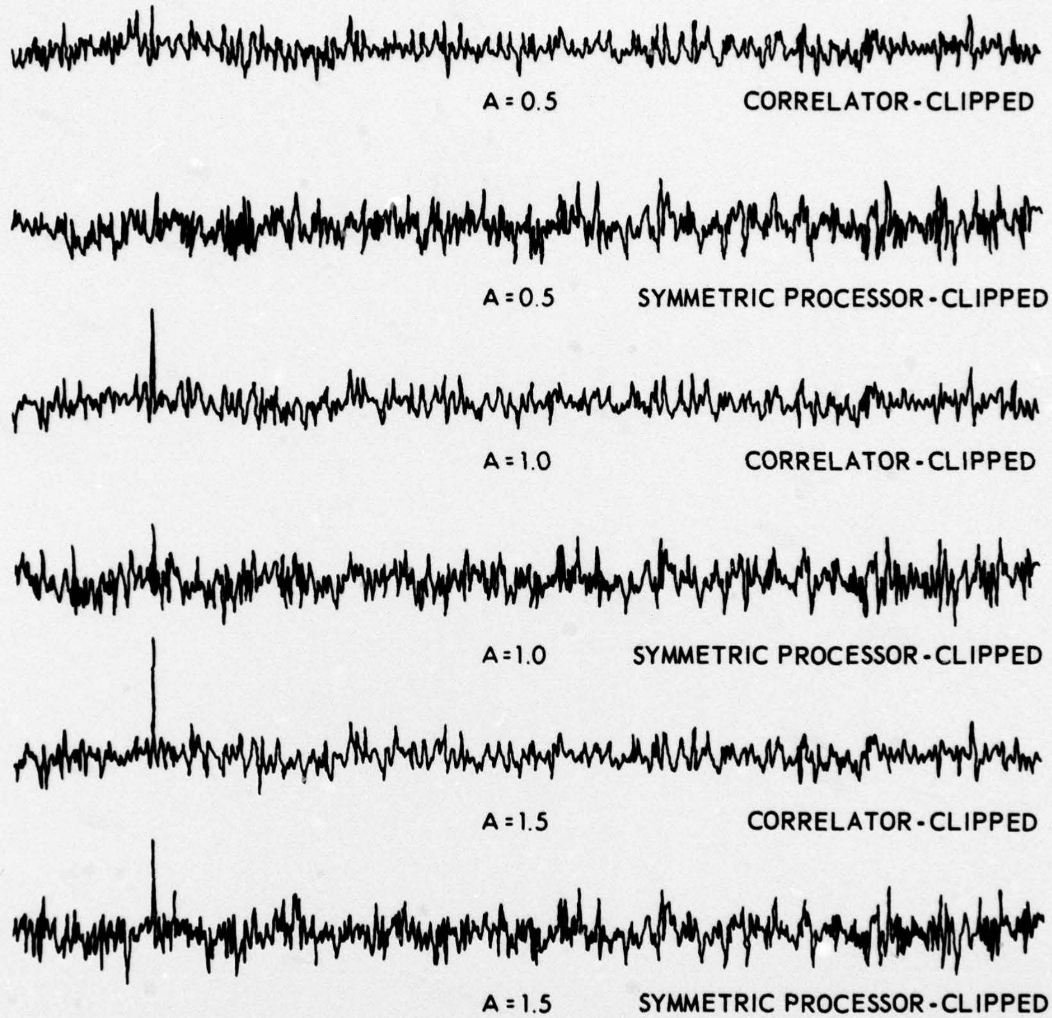

FIGURE 5
SIGNAL - TO - NOISE EFFECTS
Q = 256

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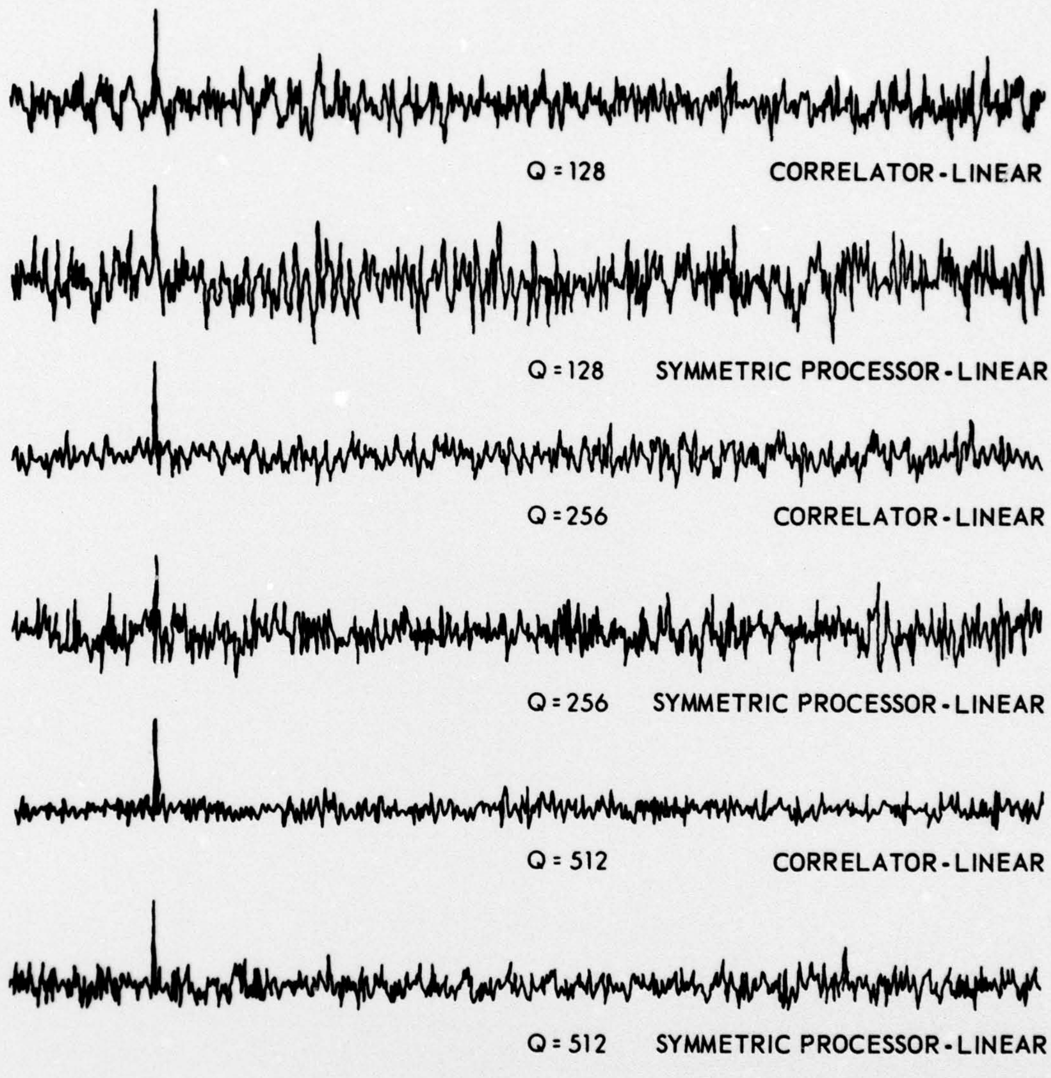

FIGURE 6
CORRELATOR LENGTH EFFECTS
A = 1.0

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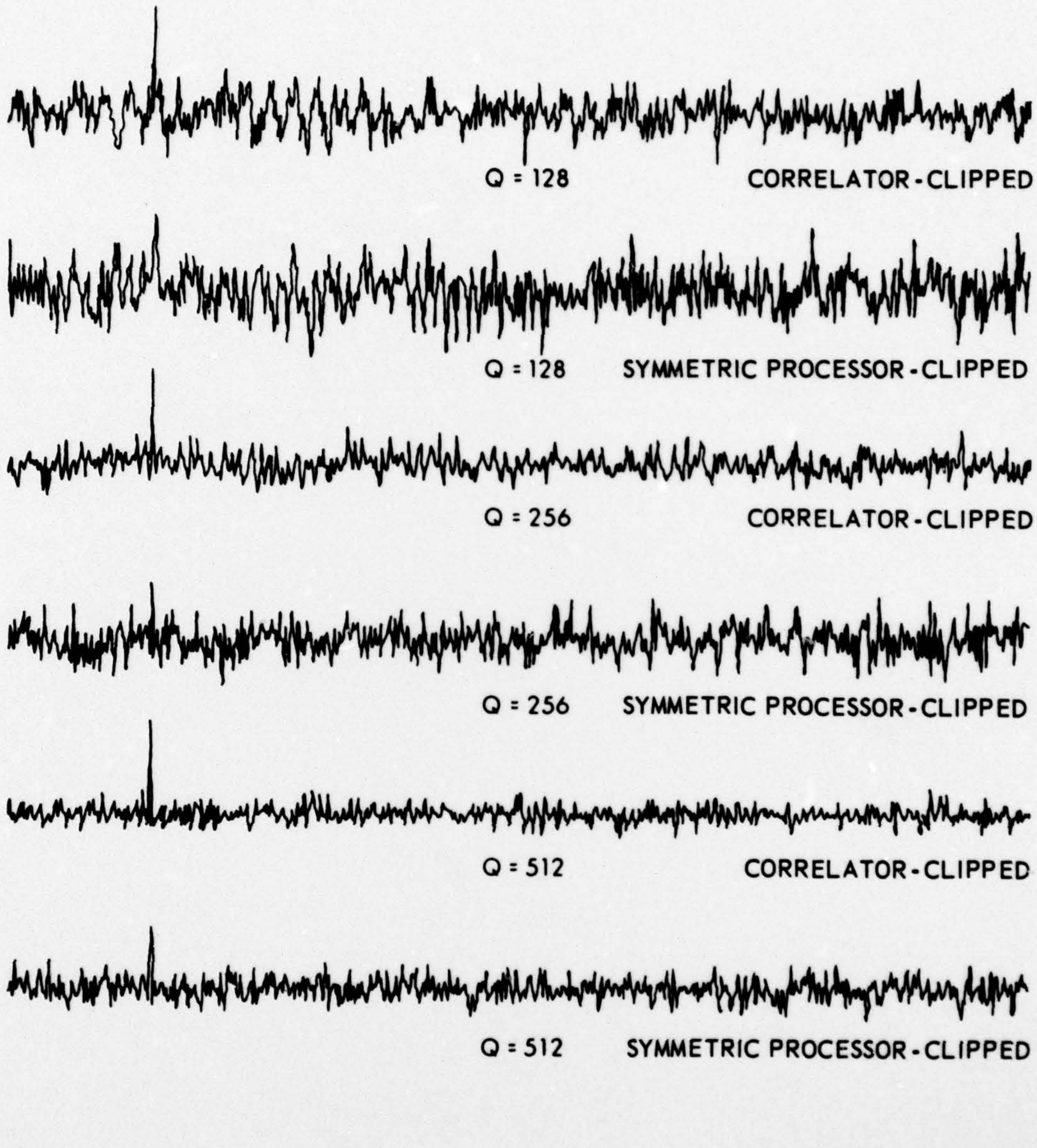

FIGURE 7
CORRELATOR LENGTH EFFECTS
A = 1.0

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GSI - RFO
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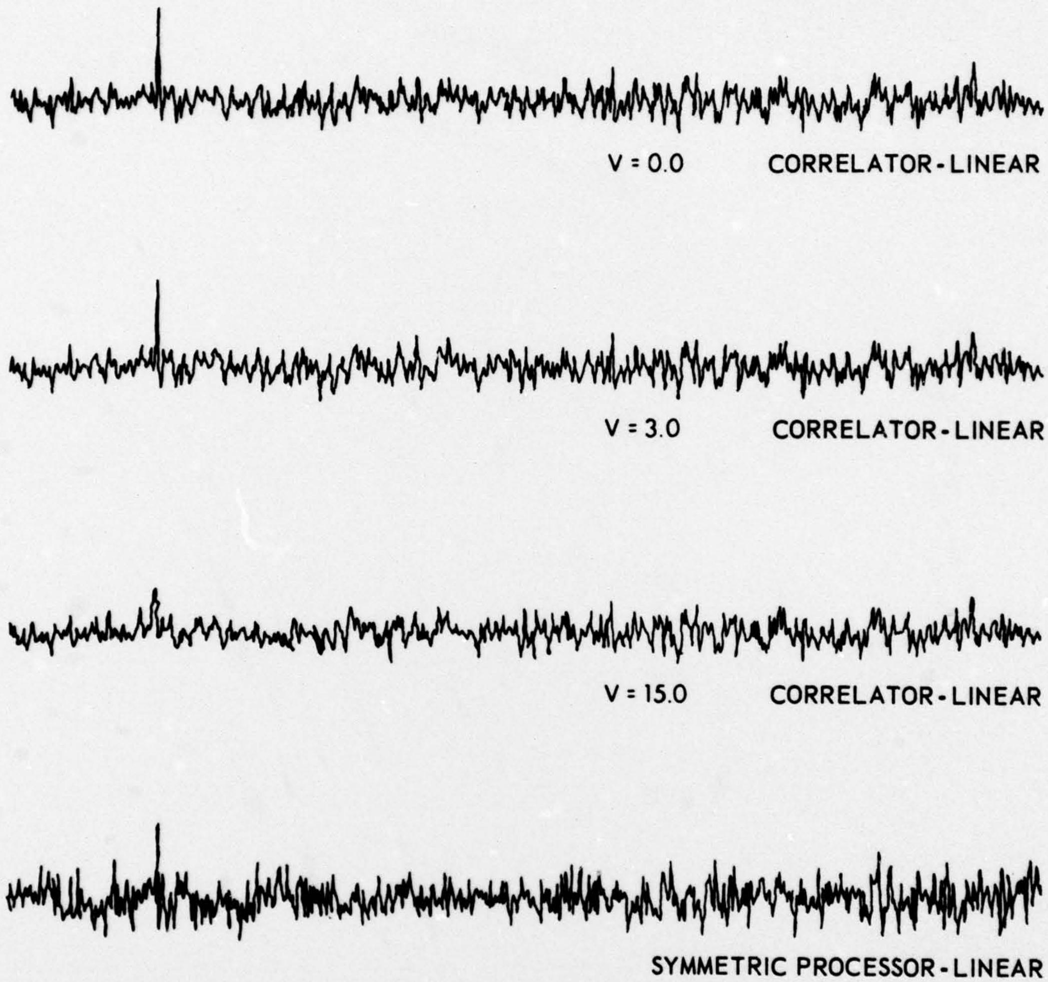

FIGURE 8
DOPPLER EFFECTS
Q = 256 A = 1.0

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DWG AS-66-1337
GSI - RFO
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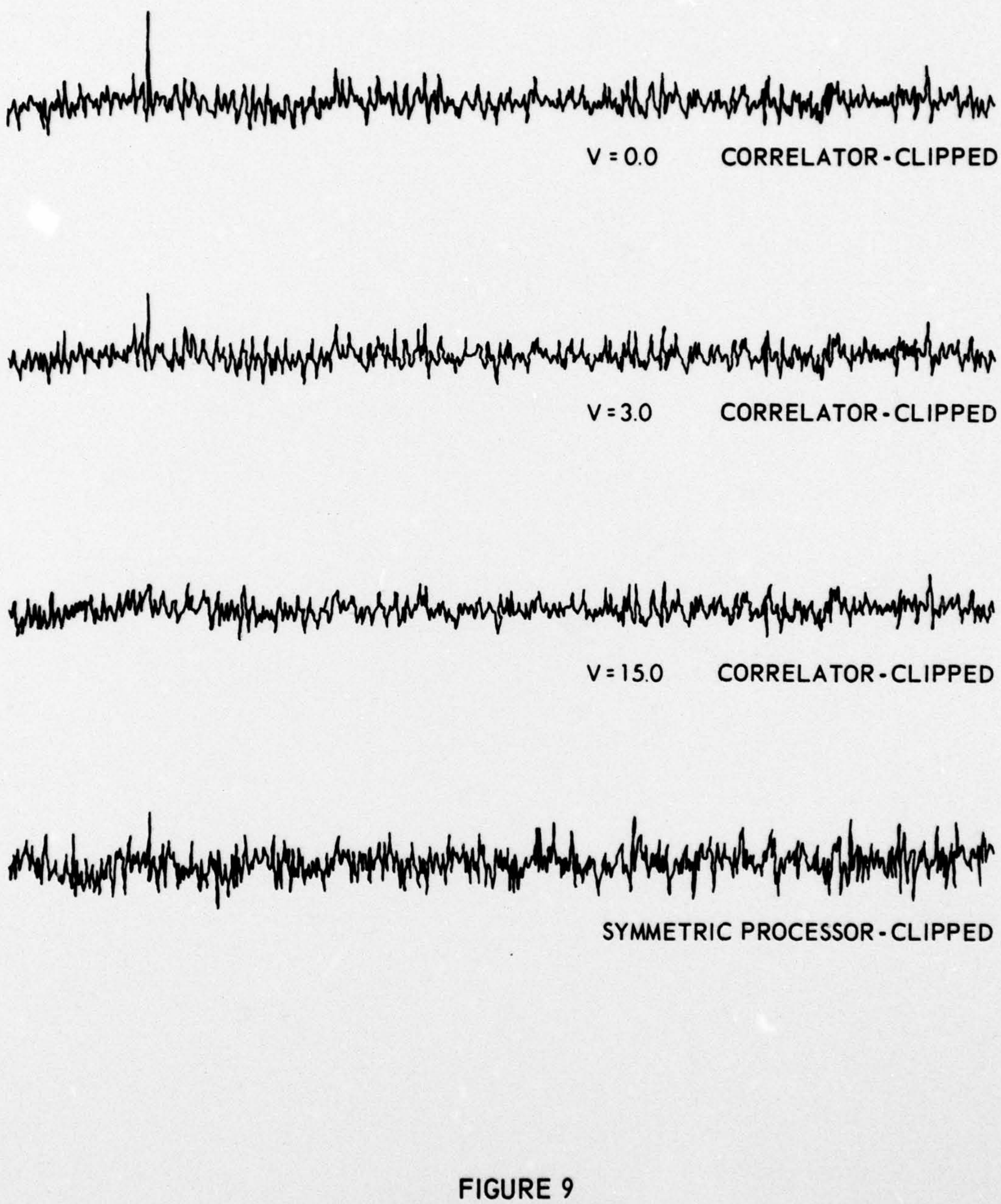

FIGURE 9
DOPPLER EFFECTS
Q = 256 A = 1.0

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DWG AS-66-1338
GSI - RFO
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discussion is applicable only to the case of the simple point reflector. If the target consists of multiple points or a continuum of reflecting surfaces then the above discussion does not apply directly.

Let us consider here only the case of multiple point reflectors. It is well known that the linear correlator yields a single peak for each of the several returns, and that clipped correlator performance is degraded by the multiple returns. It is evident from the discussion presented that if the reflectors are properly spaced and are of equal size then the received signal will again contain a symmetric signal (although not, in this case, essentially the transmitted signal), and that the output of the LSP will again be significant. For example, if

$$X(t) = AS(t) + AS(t - \Delta) + N(t) \quad , \tag{7}$$

which corresponds to two point reflectors separated in time by Δ seconds, then

$$\begin{aligned} SP(\tau) = \int_{-T}^{T} \Big\{ & A^2 S(\tau + t)S(\tau - t) + A^2 S(\tau + t)S(\tau - t - \Delta) \\ & + A^2 S(\tau + t - \Delta)S(\tau - t) + A^2 S(\tau + t - \Delta)S(\tau - t - \Delta) \\ & + F(t,\tau,\Delta) \Big\} \, dt \quad , \end{aligned} \tag{8}$$

where F contains noise factors.
The first term of Eq. (8) yields a peak of relative amplitude A^2 at $\tau=0$ corresponding to the first signal. The fourth term yields a peak of relative amplitude A^2 at $\tau= \Delta$ corresponding to the second signal. The second and third terms yield a peak of amplitude $2A^2$ at $\tau= \Delta/2$.

These three peaks appear very clearly in the first sample of Fig. 10 and somewhat less clearly in the second sample. Samples 3 and 4 of this figure

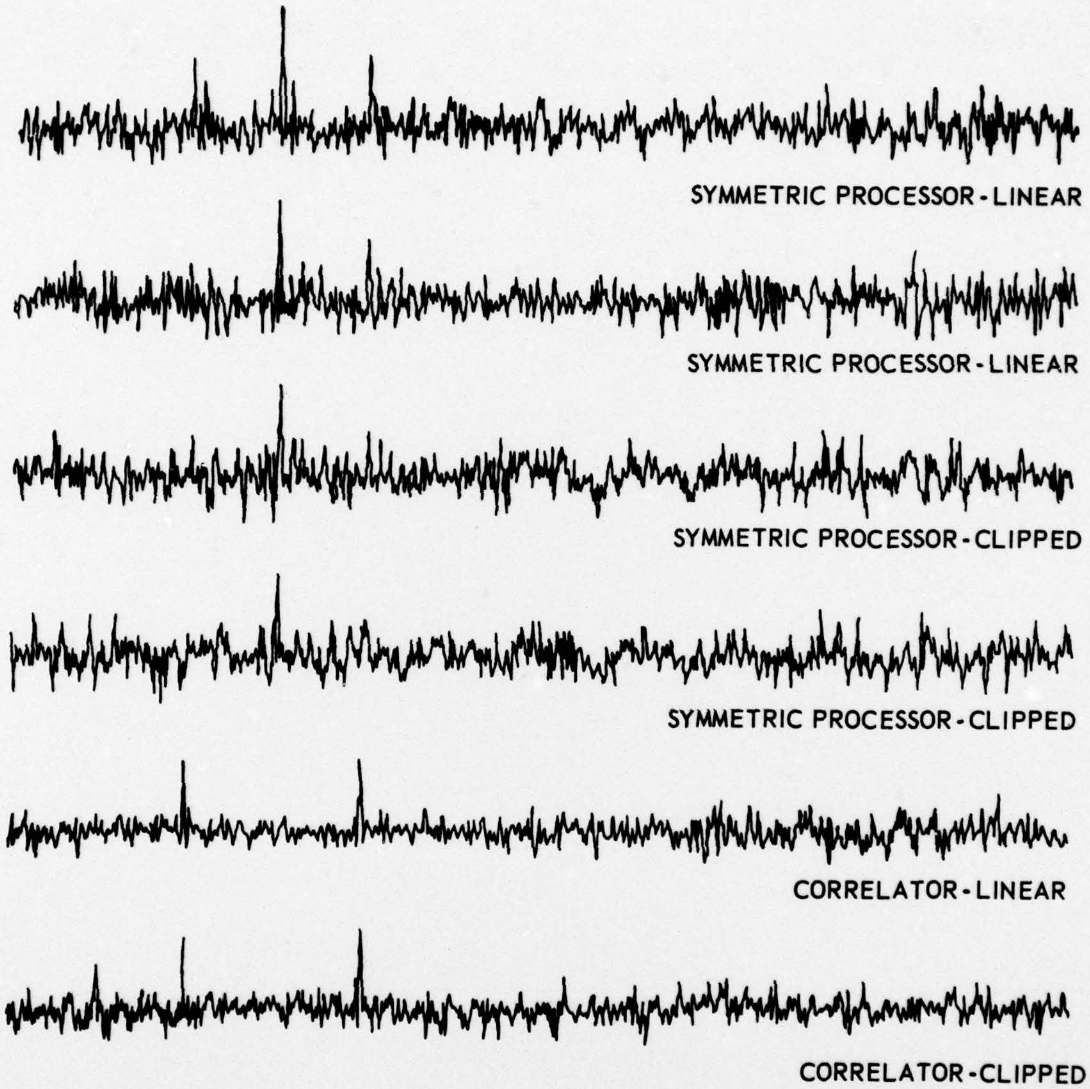

FIGURE 10
TWO - POINT TARGET
Q = 256 A = 1.0 V = 0.0

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show the clipped output. Sample 5 is the LC output, and sample 6 is the CC output. For these examples Q=256, A=1.0, and V=0.0 kt. No attempt has been made to tabulate signal-to-noise ratios for the multiple reflector case.

If there are additional reflectors that are symmetrically spaced about some time T_o and that are closely spaced relative to the signal length, then there will be symmetries that will contribute to several peaks, the largest occurring at T_o. If, however, the reflectors are not nicely located, then the situation becomes more complicated. As in Eq. (8) there will be peaks corresponding to each individual reflector, peaks corresponding to each pair of reflectors, and others resulting from each of the symmetries in the target configuration. If the signal is of length T and the target of length (in time) Δ; then the peaks from the various symmetries are limited to a time Δ (ignoring the effects of Doppler on signal duration). Thus the effects of these symmetries in the linear case is to fill in the return between the peaks caused by the individual reflectors. This effect is visible in the first sample of Fig. 11 where three identical point reflectors have been simulated. The second and third reflectors are at Δ =75 and Δ =100 relative to a T=256. In the second sample the effect is not as evident. Samples 3 and 4 show hard clipped examples and samples 5 and 6 show LC and CC performance for a similar target configuration.

D. Refinements

Two refinements of the present work may warrant consideration. First, in order to join the time inverse of a signal to the signal smoothly, so that extraordinary bandwidth is not required, the signal should terminate at a point where its slope is zero. Such points are somewhat difficult to locate accurately with analog circuits. Zeros of a waveform are, however, easier to locate. In general, the slope of a noise-like waveform will not be zero when the function is zero; thus a discontinuity in slope would occur if the signal were terminated at one of its axis crossings. If one would construct an asymmetric signal by joining the negative of the signal to the signal where the signal terminates at zero, then the resulting waveform is smooth and little

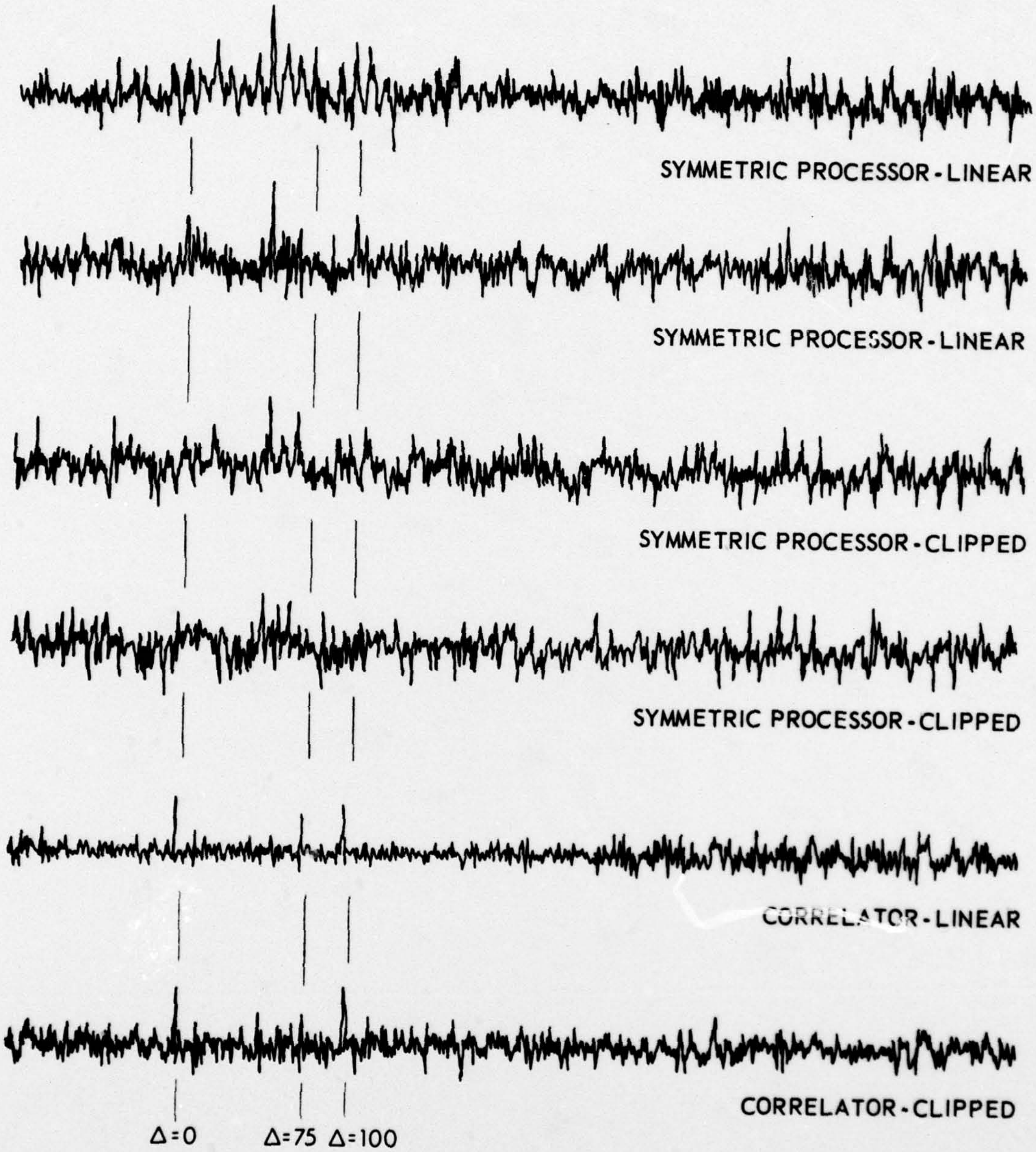

FIGURE 11
THREE - POINT TARGET
Q = 256 U = 1.0 V = 0.0

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or no bandwidth in excess of that needed for the signal is required. The discussion above is completely unchanged by this consideration of an asymmetric signal except that occasionally a minus sign may be needed. The samples shown would look essentially the same but the peaks would be negative when using Fig. 4. The tables of signal-to-noise ratios would be essentially unchanged.

Second, the assumption of low correlation between $N(t)$ and $N(-t)$ over the signal period may be a poor one. A better assumption might be that

$$2\int_{-T_o-T}^{-T_o} N(t)N(-t)\,dt = \int_{-T_o-T}^{-T_o} N(t)N(-t)\,dt + \int_{T_o}^{T_o+T} N(t)N(-t)\,dt \qquad (9)$$

is small for T_o greater than some number T_m; i.e., that sufficiently separated samples of length T were uncorrelated (one against the inverse of the other). To implement such a variation it is necessary to insert between the signal S_1 and its time increase S_2 a linear time delay and possibly another signal S_3. If S were of time duration $2T_o$, then by combining S_1, S_3, and S_2 in that order, an improvement in the signal-to-noise performance of the system might be realized.

II. CONCLUSIONS

The performance of LSP compared to LC shows definite promise for certain applications. The applicability to secure communication has not been touched at all nor have the many interesting theoretical questions that have arisen. The simplicity of the device and compatibility with an ordinary correlator may recommend it as an additional processor in any application where symmetric signals are encountered.

The real weakness of the present study is its lack of depth. Studies of the reverberation background from symmetric signals should be initiated to determine the validity of the assumptions regarding the low correlation between the background and its time inverse. Some real data should be processed through such a correlator. Some active sonar data in which a symmetric signal was transmitted are available at Defense Research Laboratory. It is planned that some of these data will be processed through the LSP to obtain some idea of the problems to be encountered when using real data. Theoretical studies relating the Doppler value at which the new device excells the correlator as a function of correlator length, signal-to-noise ratio, and clipping should be attempted.

The author is indebted to Miss Judith E. Keil for most of the programming for this study.

10 April 1967

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